CHAPTER 13

NONBUILDING STRUCTURES

13-1. Introduction. This chapter prescribes the seismic design criteria for ground located structures, other than buildings. The design will be based on SEAOC 1I and SEAOC Table 1-I Refer to chapter 12 for seismic design criteria for equipment. In some cases, equipment on the ground qualifies under this chapter.

13-2. General. Structures other than buildings are designed to resist seismic lateral forces determined in accordance with $V = (ZIC/R_w)W$ (SEAOC eq 1-1), where R_W ranges from 3 to 5 as shown in SEAOC Table 1I. Examples for obtaining the forces are in appendix F. SEAOC also includes a special equation for rigid structures ($V = 0.5$ ZIW when T is less than 0.06) and a minimum value of 0.5 for C/R_w. The period will be determined by SEAOC Method B.

13-3. Elevated tanks and other inverted pendulum structures. Structures that represent inverted pendulums, such as an elevated tank supported by a tower structure that is light in weight relative to the tank and contents, will use the basic formula $V = (ZIC/R_w)W$ with the value of R_w equal to 3. The value for W will include the effective weight of the contents. The accidental torsion will be computed as for buildings. Stresses will be computed for the earthquake forces in any horizontal direction.

a. *Elevated tanks on cross-braced columns.* Foundation piers will be interconnected by steel or reinforced concrete struts. When supported by piles or caissons, diagonal struts will also be required. For most four-legged tanks, uplift and column design is critical when the horizontal force is applied at 45 degrees to the major axes. Figure F-1 in appendix F illustrates the method of obtaining the seismic forces on a four-legged water tank, including a method for computing the period of vibration required to determine the value of C.

b. Hydrodynamic effects. In general, W will include the total weight of the contents of an elevated tank. However, properly substantiated procedures that account for the reduction of the effective weight of the liquid due to sloshing may be used. Such procedures usually result in a mathematical model that represents a two-degree-of-freedom system consisting of an effective rigid mass of liquid and an effective sloshing mass of liquid. The procedure is similar to that used for vertical tanks on the ground. In addition to designing the tower to resist the equivalent static seismic forces, the effects of the sloshing liquid on the interior of the tank will be considered.

c. Elevated tanks, pedestal-type. Pedestal-type elevated water tanks will not be permitted is Seismic Zones 3 and 4. In Seismic Zones 1 and 2, R_w will be equal to 3.

13-4. Vertical tanks (on ground). The basic formula $V = (ZIC/R_w)W$ will be used for tanks in which the liquid is rigidly contained (i.e., sloshing is prevented), for tanks holding highly viscous materials, and for pressure tanks. The value of R_w is equal to 4.0 (SEAOC Table 1-H), W is the weight plus contents, and C is equal to 2.75 unless it can be substantiated that the period T is greater than 0.3 second. For tanks where the liquid is not rigidly contained, the hydrodynamic effects of the sloshing liquid may be considered in order to reduce the effective mass and determine the effective centroid of the liquid.

a. Hydrodynamic effects. During an earthquake there is a complex redistribution of pressures in a tank. The design procedure for considering these hydrodynamic effects is based on a simplified procedure described in technical publications and modified herein. The effective force distribution is illustrated in figure 13-1. The liquid is divided into a constrained portion and an in-motion portion. (If h is less than 1.5R, there is no constrained liquid.) Part of the in-motion liquid, combined with the constrained liquid, forms the effective mass of the impulsive force P_I ($P_1 + P_2 = P_I$). The remaining portion of in-motion liquid forms the mass for the convective force P_c. P_I and P_c are the resultant forces of the horizontal pressures on the sides of the tank. P_I represents the force of the effective mass of liquid that moves rigidly with the tank, and P_c represents the force of the effective mass of the sloshing liquid. In addition to P_1 and P_c, there is a vertical couple, M_b, acting on the bottom of the tank due to the unbalanced vertical pressures (P_b). Bending and overturning moments are determined by multiplying P_I and P_c by the effective heights h_I and h_c, respectively. In order to include the effects of M_b below the tank base, modified effective heights, h'_I and h'_c are given.

(1) *Rigid body forces.* The rigid body forces (fig 13-2) include the seismic forces due to the impulsive liquid, the walls of the tank, and the roof. The term *rigid body* is used to denote the impulsive liquid moving rigidly with the tank. Actually, the tank does have some flexibility depending on the

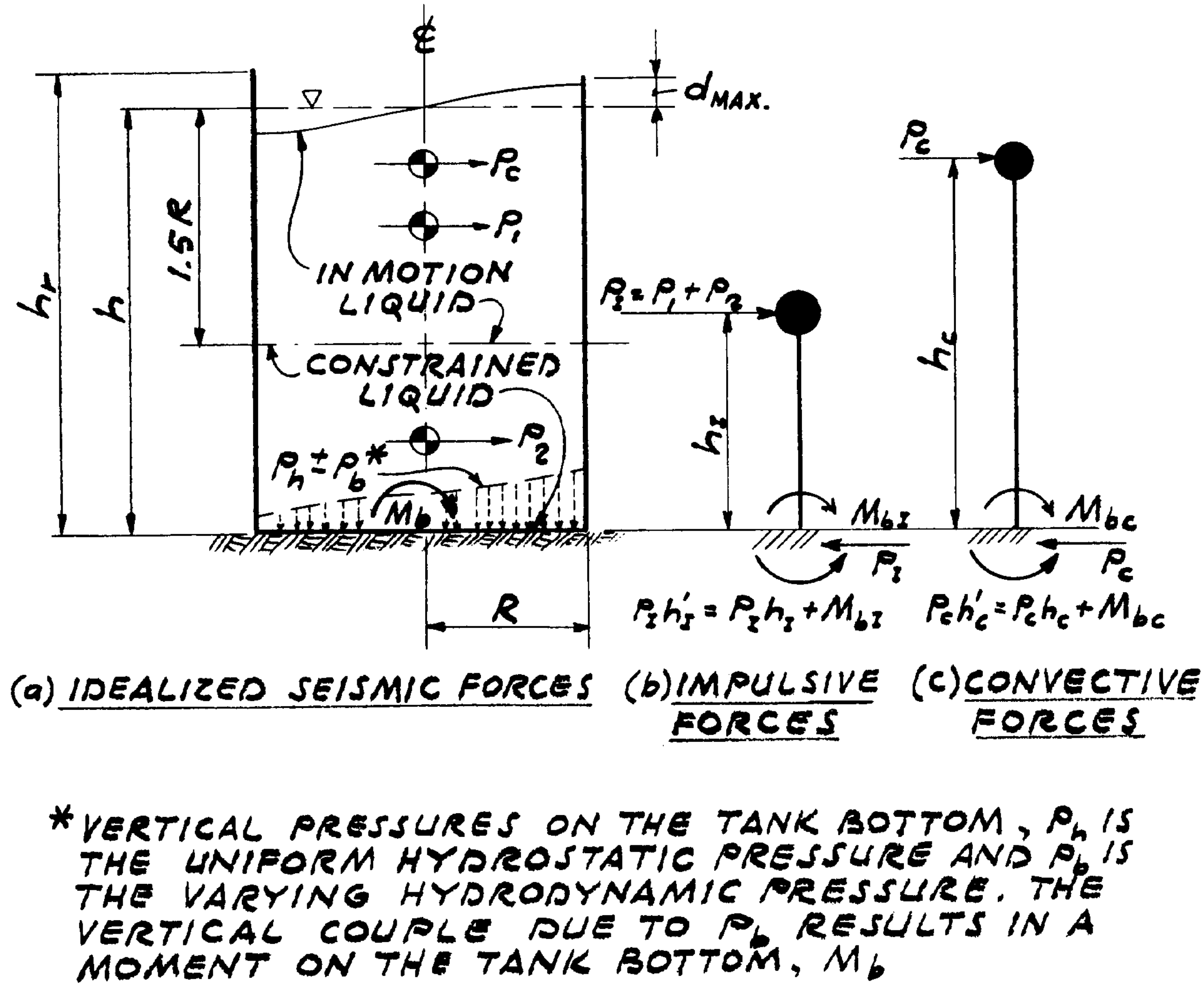


Figure 13-1. Effective Liquid force distribution.

size and shape. For calculating C it will be assumed that the period of the tank and contents is less than 0.3 second unless substantiated to be longer.

(a) The total horizontal rigid body force, V_{RB}, will be determined by the equation

$$V_{RB} = (ZIC/R_w)\,(W_r + W_w + W_I) \qquad \text{(eq 13-1)}$$

where Z and I are prescribed in chapter 3, R_w equals 4.0, and C equals 2.75 unless a lower value is substantiated. W_r is the weight of the roof (if any), W_w is the weight of the tank walls, and W_I is the weight of the impulsive liquid. W_I is determined from the effective weight ratio, W_I/W, in figure 13-3 or table 13-1, where W is the total weight of the liquid.

(b) The moments at the base of the tank are determined by the equation

$$M_{RB} = (ZIC/R_w)\,(W_r h_r + W_w \bar{h}_w + W_I h_I) \qquad \text{(eq 13-2)}$$

where h_r is the height of the roof, $\bar{h}_w$ is the height to the center of mass of the tank walls, and h_I is the effective height of the impulsive liquid. h_I is determined from the effective height ratio h_I/h in figure 13-3(b) or table 13-2, where h is the height of the water level (at rest). To calculate stresses in the tank wall, where M_b is not effective, use h_I. Below the tank base, where M_b is effective, use h'_I.

(2) Sloshing liquid forces (fig 13-2).

(a) The sloshing liquid forces V_{SL} are equal to the convective force, P_c, and will be determined by the equation

$$V_{SL} = (ZIC/R_w)W_C \qquad \text{(eq 13-3)}$$

where Z, I, and R_w are the same as used in equation 13-1. C is dependent on the sloshing period T and the site coefficient S (SEAOC Table 1B). W_C, the weight of the convective liquid, is determined from the effective weight ratio, W_C/W, in figure 13-3 or table 13-1, where W is the total weight of the liquid.

(b) The sloshing period is determined by the equation

$$T = k_T\sqrt{h} \qquad \text{(eq 3-14)}$$

where k_T is determined from figure 13-4 or table 13-3.

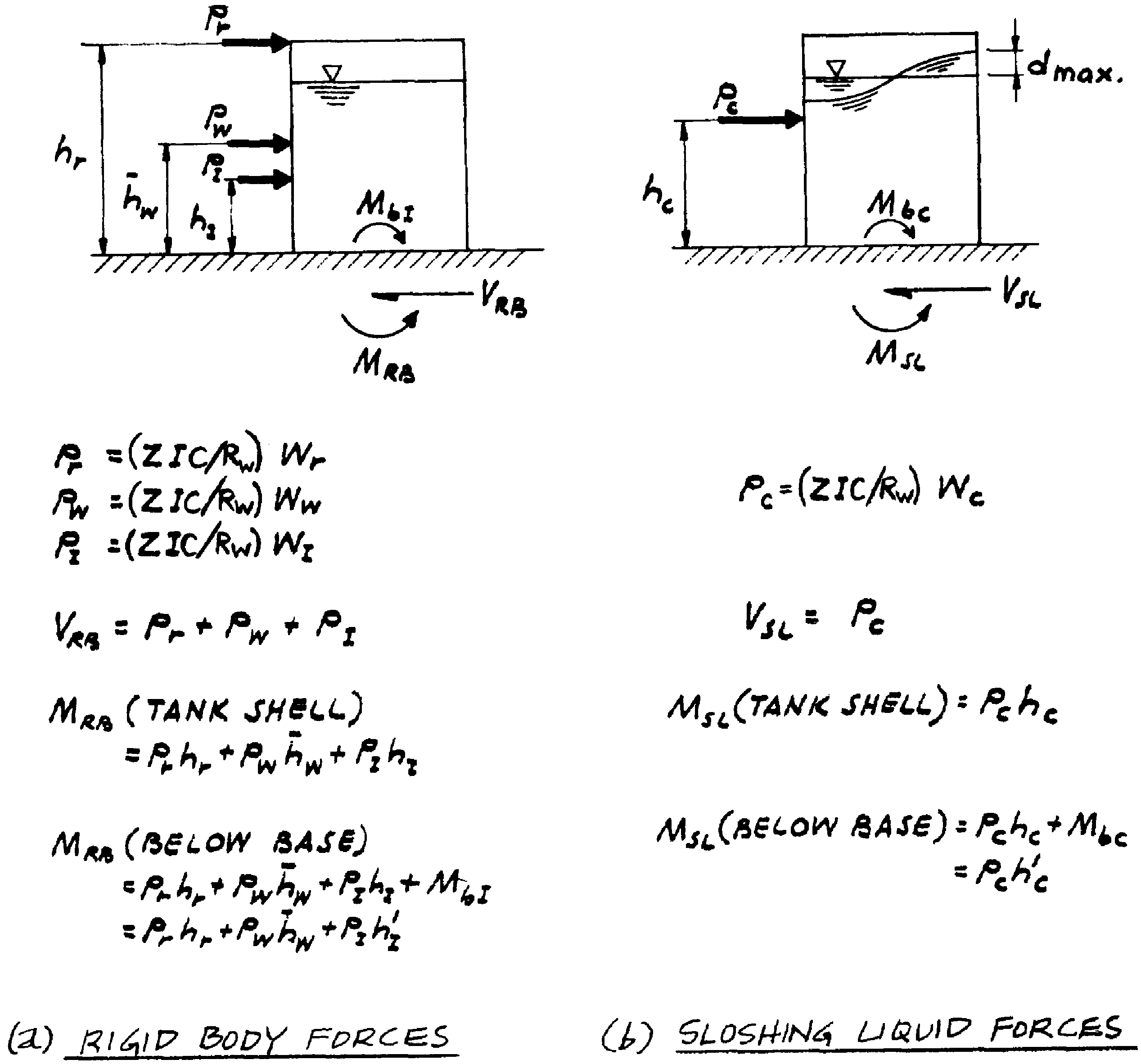


Figure 13-2. Rigid body and sloshing liquid forces.

(c) The moments at the base of the tank are determined by the equation

$$M_{SL} = (ZIC/R_w)W_c h_c \quad \text{(eq 13-5)}$$

where h_c is the effective height of the convective liquid; h_c is determined from the effective height ratio h_c/h (fig 13-3(b) or table 13-2), where h is the height of the water level (at rest). To calculate stresses in the tank wall, where M_b is not effective, use h_c. Below the tank base, where M_b is effective, use h'_c.

(d) The maximum design height of the sloshing wave is determined for cylindrical tanks from the equation

$$d_{max} = \frac{0.75(ZIC/R_w)R}{1 - k_d(ZIC/r_w)} \quad \text{(eq 13-6)}$$

and for rectangular tanks from the equation

$$d_{max} = \frac{0.833(ZIC/R_w)R}{1 - k_d(ZIC/r_w)} \quad \text{(eq 13-7)}$$

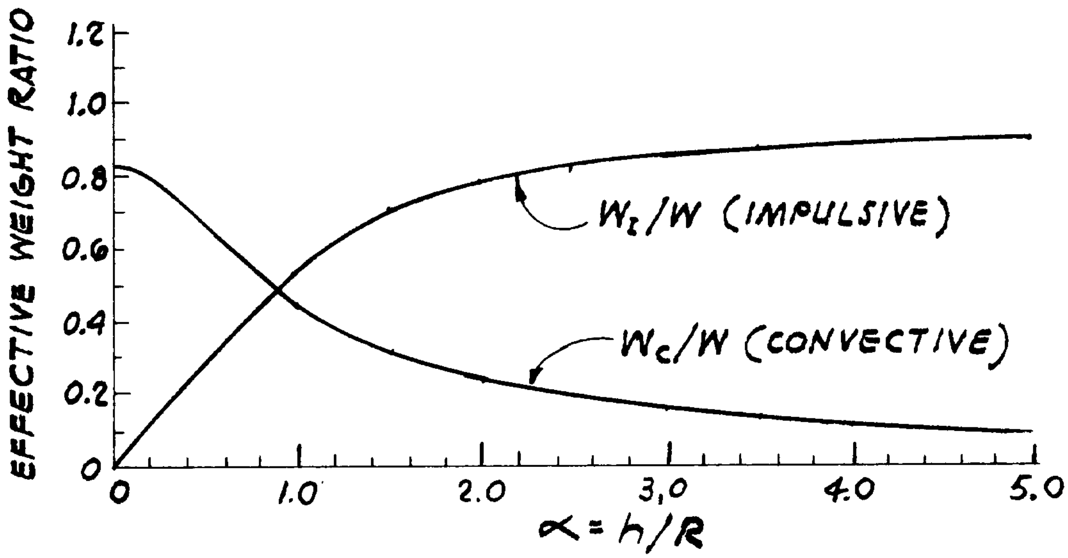
where k_d is obtained from figure 13-5 or table 13-4. R is the radius of a cylindrical tank or one-half the plan dimension of a rectangular tank.

(3) Combining the rigid body forces and the sloshing liquid forces. The rigid body forces and the sloshing forces will be combined by the square root of the sum of the squares, as shown in the equations

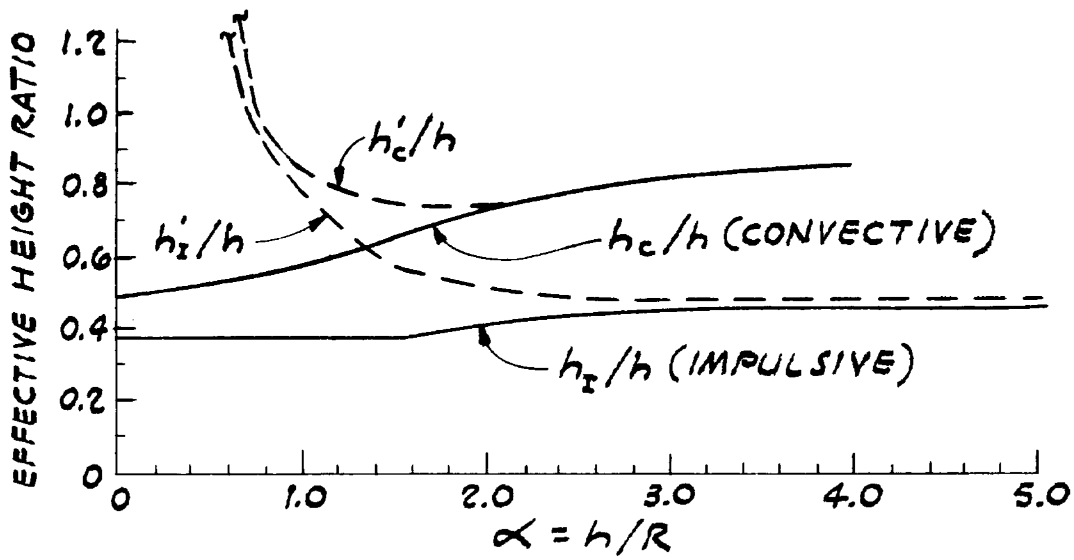
$$V_{total} = \sqrt{V_{RB}^2 + V_{SL}^2} \quad \text{(eq 13-8)}$$

and

$$M_{total} = \sqrt{M_{RB}^2 + M_{SL}^2} \quad \text{(eq 13-9)}$$



(a). Effective Weight Ratio (See Table 13-1)



(b). Effective Height Ratio (See Table 13-2)

Figure 13-3. Effective weight and height ratios.

α		0.50	0.75	1.00	1.50	2.00	2.50	3.00	3.50	4.00	5.00
W_I/W, impulsive		0.29	0.42	0.54	0.71	0.79	0.83	0.86	0.88	0.89	0.91
W_C/W, convective	Cylindrical	0.66	0.53	0.43	0.30	0.23	0.18	0.15	0.13	0.11	0.09
	Rectangular	0.69	0.58	0.48	0.34	0.26	0.21	0.18	0.15	0.13	0.11
See Figure 13-3(a) for Plot											

Table 13-1. Effective weight ratio.

α		0.50	0.75	1.00	1.50	2.00	2.50	3.00	3.50	4.00	5.00
h_I/h, impulsive		0.38	0.38	0.38	0.38	0.41	0.42	0.44	0.45	0.45	0.46
h'_I/h, impulsive		1.60	1.00	0.80	0.58	0.51	0.49	0.48	0.48	0.47	0.47
h_C/h, convective	cylindrical	0.53	0.57	0.60	0.68	0.74	0.79	0.82	0.84	0.86	0.89
	rectangular	0.53	0.55	0.58	0.65	0.71	0.76	0.79	0.82	0.84	0.87
h'_C/h, convective	cylindrical	1.60	0.96	0.79	0.73	0.75	0.79	0.82	0.84	0.86	0.89
	rectangular	2.00	1.11	0.86	0.73	0.74	0.77	0.80	0.82	0.84	0.87
See Figure 13-3(b) for Plot											

Table 13-2. Effective height ratio.

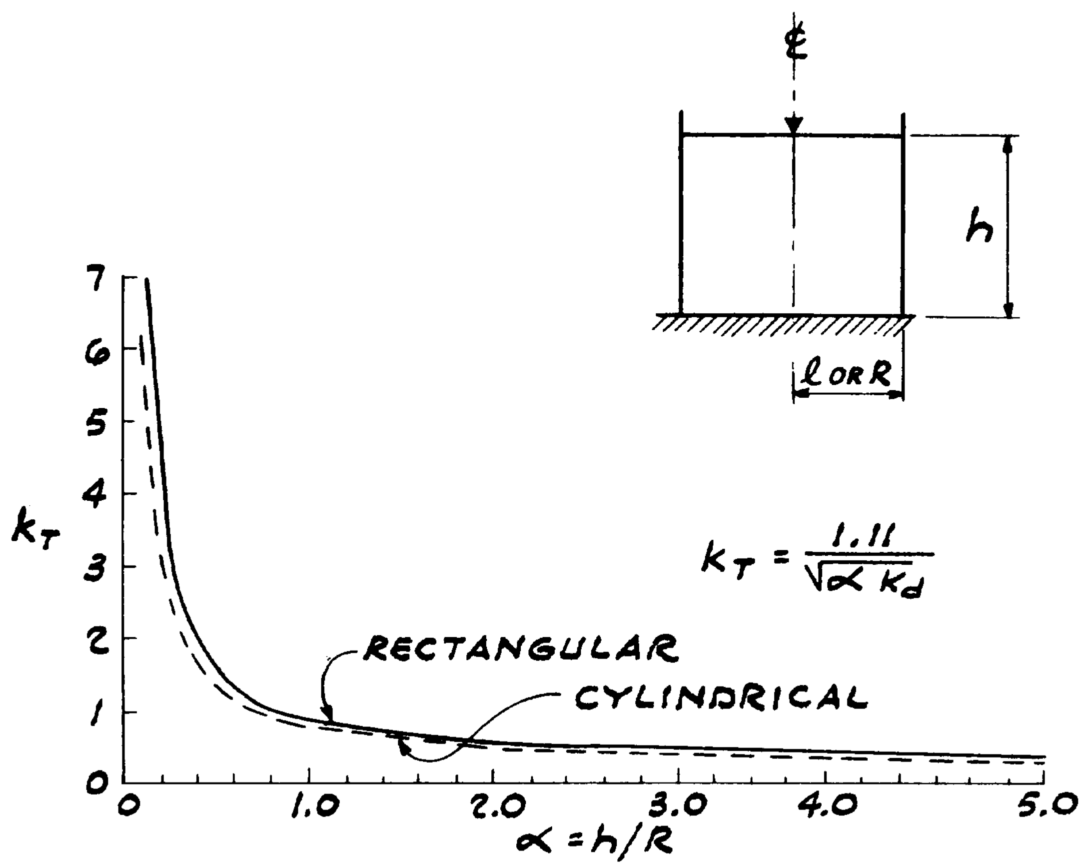


Figure 13-4. Period constant, k_T

This is consistent with modal analysis procedures where spectral responses of the predominant modes are combined in such a manner.

(4) Sloshing wave height The value of d_{max} must be less than the freeboard height (h_r minus h) for the simplified hydrodynamic procedure to be valid. If d_{max} is greater than (h_r minus h), liquid will overflow the top of the tank when there is no roof or will be confined by the roof if a roof exists. When there are interior elements, such as baffles or roof supports, the effects of sloshing liquid on these elements will be considered.

b. Design of tank. The critical items of concern in the seismic design of the tank are the horizontal shear at the base, the overturning and uplift forces at foundations, the compression buckling of the tank shell, and, when tie-downs are used, the resulting additional stresses at the attachment of

	k_T*								
α	0.50	0.75	1.00	1.50	2.00	2.50	3.00	4.00	5.00
k_T, cylindrical	1.40	1.00	0.84	0.67	0.58	0.52	0.47	0.41	0.37
k_T, rectangular	1.50	1.10	0.92	0.73	0.63	0.56	0.51	0.44	0.39

*used for sloshing (convective motion) period: $T = k_T\sqrt{h}$, where h is the height in feet.
See Figure 13-4 for Plot

Table 13-3. Period constant, k_T

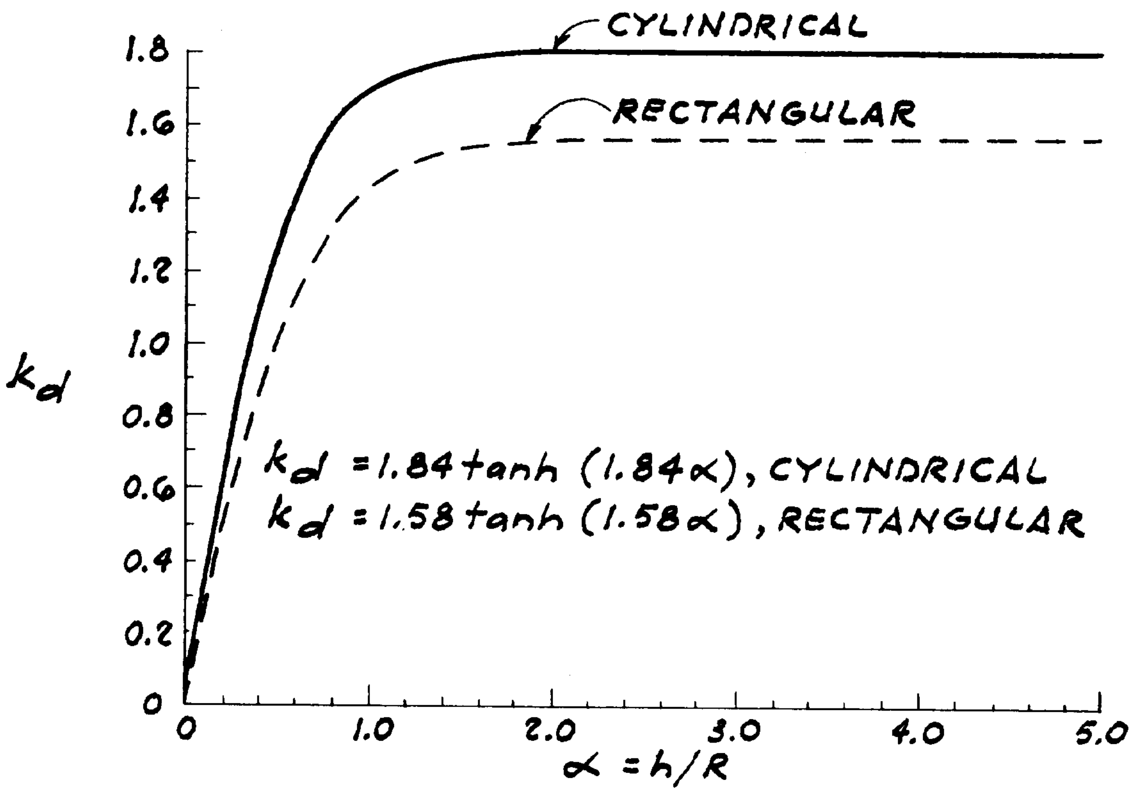


Figure 13-5. Coefficient k_d.

α	0.50	0.75	1.00	1.50	2.00	2.50	3.00	4.00	5.00
k_d, cylindrical	1.33	1.62	1.75	1.83	1.84	1.84	1.84	1.84	1.84
k_d, rectangular	1.04	1.31	1.45	1.55	1.57	1.58	1.58	1.58	1.58

See Figure 13-5 for Plot

Table 13-4. Coefficient k_d.

the anchors, which could tear the shell. The stresses resulting from the seismic forces will be combined with other applicable stresses. Procedures for the design of vertical tanks are beyond the scope of this manual. Industry standards (e.g., AWWA and API) have developed seismic criteria as supplements to general design criteria. Procedures used for the design of tanks will be substantiated by means of rational analysis, tests, or past experience.

13-5. Horizontal tanks (on ground). The basic formula $V = (ZIC/R_w)W$ will be used, with $R_w = 4$.The critical items of concern in the seismic design are the stresses in the saddles and in the base footing. The soil pressure in the transverse direction due to overturning may be critical. The resultant of forces must always fall within the middle third of the footing pad.

13-6. Retaining walls. The design of retaining walls for seismic forces in Seismic Zone 4 will use an additive seismic factor of 20 percent of the total earth pressure forces plus 20 percent of the weight of the wall at a point 2/3 the fill height above the base of the retaining wall. The stresses in the concrete and reinforcing steel will not be critical, as the increase in stresses or decrease in load factor is greater than the increase due to seismic load. The overturning effect on the footing may be critical in some cases. The footing will be sized so that there is no theoretical net tension between the footing and the supporting ground. In Seismic Zones 1, 2, and 3, the 20 percent factor will be proportioned in the ratio of the Z factor to 0.4.

13-7. Buried structures. Buried tanks and pipes of moderate size, or smaller, generally do not require special seismic design considerations if applicable nonseismic design criteria are satisfied. However, tanks, tunnels, pipes, etc. that have large cross sections or are classified for essential or important usage will require special considerations for seismic design that are not included in the scope of this manual. In the design of long structures, consideration will be given to the wave shape and ground deformation resulting from the seismic ground motion. Where changes in the support system, configuration, or soil condition occur, flexible couplings will be provided in order to accommodate the anticipated deformation, as discussed in chapter 14.